Title of Investigation:

10 mK Detector Cooling

Principal Investigator:

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Other In-house Members of Team:

Dr. Michael DiPirro (Code 552), Dr. Dominic Benford (Code 665)

Other External Collaborators:

Prof. Naresh Dalal (Florida State University) and Dr. Trevor Riedmann (Ames Laboratory)

Initiation Year:

FY 2005

Aggregate Amount of Funding Authorized in FY 2004 and Earlier Years:

$0

Funding Authorized for FY 2005:

$40,000

Actual or Expected Expenditure of FY 2005 Funding:

In-house: $5,000 for fabrication; $10,000 for liquid helium for testing. Contracts: Inter-agency agreement with Ames Laboratory, Iowa, for fabrication of $PrCu_6$. Grants: $10,000 to Professor Naresh Dalal (Florida State University) for trial production of peroxychromate compounds

Status of Investigation at End of FY 2005:

Continued into 2006 with IRAD funding

Expected Completion Date:

End of FY 2006

DDF annual report

Purpose of Investigation:

Upcoming far-infrared (IR) space missions are faced with a very challenging requirement: making detectors with sufficient sensitivity to be limited only by the photon noise present in the darkness of space. Superconducting bolometers are the only technology likely to achieve this in the near future, using either very small structures or phonon-electron decoupling in low volume thermistors. Regardless of which type is used, it is estimated that these detectors will have to be cooled to approximately 20 mK (two hundredths of a degree above absolute zero) to achieve the required sensitivity. The goal of this project is to develop a refrigerator that can cool to 10 mK and that can be qualified for use in space.

The starting point is an existing 4-stage adiabatic demagnetization refrigerator (ADR), shown below, that can cool continuously at 50 mK. Lower temperature can be achieved by adding another stage at the cold end, which has the ability to cool from 50 mK down to 10 mK. Cooling is achieved through the use of a superconducting magnet that surrounds a magnetic material. Increasing the magnet's field aligns the magnetic spins in the material, causing them to give off heat. When the material is subsequently demagnetized, the spins absorb heat and the material cools down. The challenge is to identify (or develop) materials with low enough spin density to be able to cool to 10 mK or below. Materials currently in use can cool only to about 20 mK, and at that point they are not efficient.

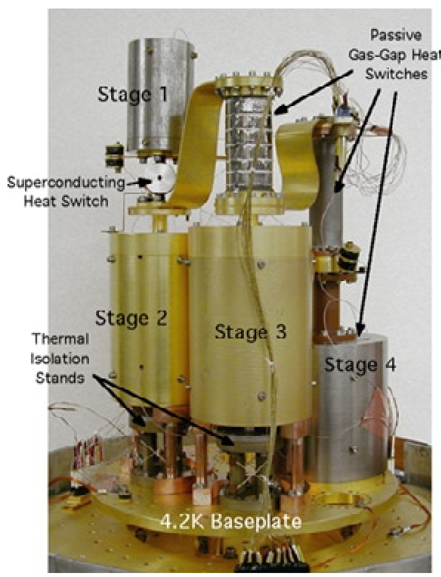


Figure 1. 4-stage CADR used as a testbed for 10 mK stages

Accomplishments to Date:

Three different materials were chosen for possible use in the 10 mK CADR: cerium magnesium nitrate (CMN), $PrCu_6$, and a peroxychromate compound. The goal for each is the same: maximizing the cooling capacity at 10 mK, while packaging the material in a way that promotes efficient heat transfer in and out during the ADR cycle. The latter is vitally important since thermal boundary resistances tend to become exceedingly large at such temperatures, and a perfectly functioning refrigerant can be rendered useless if it thermally decouples from the device it is ostensibly cooling.

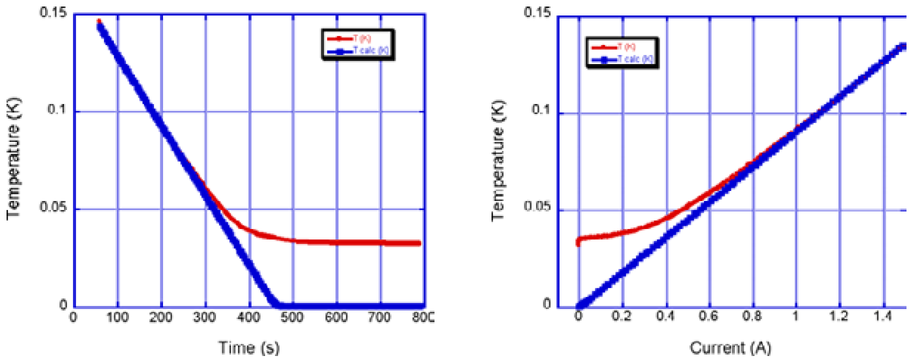
The three candidates have very different magnetic, thermal, and chemical properties. This was a deliberate choice, intended to widen the scope of materials considered for use in ADRs and potentially identify materials that are superior for other temperature regimes. As a hydrated salt, CMN is the most conventional. Like other salts used in the 4-stage ADR, it is grown from a solution onto a matrix of copper wires that constitute the thermal interface. Also like them, it has to be hermetically sealed in a container to prevent dehydration. Fabrication was straightforward, but because CMN has the lowest entropy density and worst thermal boundary resistance, it was used more as a tool to assess issues like ultra-low temperature thermometry, stray heat loads and fringing magnetic fields, and the need for auxiliary shielding from these.

The greatest potential was seen to lie in the nuclear paramagnets, of which we chose $PrCu_6$, and the peroxychromate compounds. None of these materials requires hermetic packaging, which greatly simplifies the construction of an ADR stage. Both have significantly higher entropy capacity than CMN. $PrCu_6$ has the further advantage that it is metallic, which greatly reduces the problem of transferring heat into and out of it.

Manufacture of these two materials has been the principal challenge. $PrCu_6$ is produced by arc-melting, a process that often results in internal fractures due to large thermal stresses as it cools. For us, this would severely degrade heat-transfer efficiency; so Ames Laboratory worked on the process to finally produce uniform, large samples. One is shown below after it was machined at Goddard to provide a means of clamping the material to a thermal interface and minimizing eddy current heating. Testing on it will begin shortly. For the peroxychromates, only very small samples had previously been produced, and these showed excellent magnetic properties for our use. FSU was engaged to develop a process for producing large (100-gram) quantities that can then be integrated with a thermal bus. Delays in establishing the grant prevented the delivery of the first samples before the end of FY 2005.

Figure 2. PrCu6 sample at left; integrated with a thermal interface at right

The CMN salt pill was integrated with the 4-stage CADR to conduct single-shot cooling tests to 10 mK. The salt is initially magnetized at some temperature from 60–100 mK, to a modest magnetic field of 0.2 tesla. While being magnetized, it generates heat that is absorbed by an adjacent stage. The salt is then thermally isolated and demagnetized adiabatically, causing the salt to cool. A typical cooling curve is shown below, both as a function of time and of the applied magnetic field. Of particular note is the expected proportional relationship between field and temperature down to about 60 mK, but the subsequent plateau at about 30 mK. The equilibration time for reaching steady state indicates that the discrepancy between observed and expected temperatures is due to poor thermal coupling between the salt and the thermal bus—a problem that was anticipated, but not of this magnitude. Future work will concentrate on the $PrCu_6$ material since thermal boundary resistances should less of an issue.



Papers for Presentation at Professional Society Meetings, Seminars, Symposia:

Peter Shirron, Don Wegel and Michael DiPirro, "A Continuous Adiabatic Demagnetization Refrigerator for Cooling to 10 mK and Below," accepted for publication in the proceedings of LT24, the 24th International Conference of Low Temperature, Orlando, FL, July 2005.

Peter Shirron, Don Wegel, Michael DiPirro, and Sarah Sheldon, "An adiabatic demagnetization refrigerator capable of continuous cooling at 10 mK and below," accepted for publication in the proceedings of LTD-11, the 11th International Conference on Low Temperature Detectors, August 2005, Tokyo, Japan.

Peter Shirron, "Detector Cooling Options for Temperatures as Low as 10 mK," accepted for publication in the proceedings of the Society of Photo-optical and Instrument Engineers, July 2005, San Diego, CA.

Planned Future Work:

Continuation of the work under IRAD funding is proceeding. The focus is now on conducting the same cooling runs with the $PrCu_6$ compound, and eventually constructing two stages from this material to demonstrate continuous cooling at 10 mK. Ultimately, the ADR will be the basis of a cooling system for future IR and X-ray astronomy missions.

Key Points Summary:

Project's innovative features: The multi-stage ADR is a versatile technology for low- temperature cooling. In particular, it is well suited to future missions that will use mechanical refrigerators for the upper-cooling stages instead of liquid cryogens. The ability to expand the number of stages to access lower temperatures makes it possible to reach temperatures of 10 mK or lower in space.

Potential payoff to Goddard/NASA: This technology, coupled with detector-development efforts, makes Goddard extremely competitive (if not uniquely capable) in the field of low- temperature astronomy, which ultimately will result in successful proposals for IR and X-ray missions.

The criteria for success: The ability to cool continuously at 10 mK is the current performance goal, although any temperature below the current "best" of 60 mK in space will result in improved detector performance.

Technical risk factors: The primary risk in this development centered on achieving sufficiently good thermal contact between the refrigerant and components being cooled. This risk remains, but should be retired with the introduction of the $PrCu_6$ material.